Precision SUSY and the GUT Scale

G. A. Blair
Dept of Physics, Royal Holloway, Univ. of London, Egham, Surrey. TW20 0EX. UK.

Precision measurements from the Large Hadron Collider and International Linear Collider will provide a detailed picture of physics at the TeV scale. The particle spectrum at the TeV scale can then be evolved via the renormalization group equations to the grand unified scale, where the underlying structure of nature may be revealed. The key principles involved in this procedure are outlined and some representative analyses presented.

1. INTRODUCTION

The startup of the Large Hadron Collider (LHC) in 2007 will open a new view to physics at the TeV scale and should reveal the key mechanisms behind the breaking of electroweak symmetry, by which the particles of the standard model (SM) gain their masses. The grouping of matter particles into multiplet representations of higher groups, as discussed in Section 2, suggests that Grand Unified Theories (GUTs) based on these higher groups may play a role at high energy scales. Precision measurements at experimentally accessible energy scales can reveal the structure of physics at higher energy scales by extrapolation using the Renormalization Group Equations (RGEs), as described in Section 3.

The symmetry breaking mechanism, discussed in Section 4, is commonly associated with a fundamental scalar field, ϕ, called the Higgs field which, if found at the LHC, will be the first such scalar field to be discovered. If a fundamental scalar Higgs is indeed behind electroweak symmetry breaking then the question arises of why its mass is so light. A possible solution, supersymmetry (SUSY) is introduced in Section 5, together with a discussion of how SUSY is broken. The presence of SUSY in nature would lead to spectacular discoveries at the LHC and International Linear Collider (ILC) and some representative experimental prospects are presented in Section 6. In Section 7 the use of bottom-up extrapolation via RGEs is presented for a few select scenarios in order to reveal how this technique may reveal the structure of nature at very high energy scales.

2. STANDARD MODEL MATTER FIELDS

The matter fields f of the SM consist of quarks and leptons, together with their anti-particles. An anti-particle can be described by the conjugate field f^c of the corresponding matter particle, which enables each generation of matter particles to be arranged in suggestive multiplets, such as shown in Equation 1:

$$\begin{pmatrix} 0 & u_1^c & -u_2^c & u_3 & d_3 \\ & 0 & u_3^c & u_2 & d_2 \\ & & 0 & u_1 & d_1 \\ & & & 0 & e^c \\ & & & & 0 \end{pmatrix}, \begin{pmatrix} d_3^c \\ d_2^c \\ d_1^c \\ e \\ \nu_e \end{pmatrix} \tag{1}$$

The fact that it is possible to arrange the SM fields into such multiplet forms suggest that the matter fields may be representations of higher groups, such as SU(5) in the arrangement of Eq.1. Even higher groups such as SO(10) are now attractive in order to include conjugate fields for the neutrino (as may be needed to explain neutrino masses), or groups such as E_6, which arise naturally in string theories.

3. RENORMALISATION GROUP EQUATIONS

The gauge field theoretical description of particles and interactions associates a bare fermionic field, ψ_0 with each particle and a bare gauge field A_0 for each interaction, described by a bare Lagrangian L_0 including bare masses m_0 and couplings g_0 such as represented in Equation 3:

$$L_0 = i\overline{\psi}_0\gamma_\nu\partial^\nu\psi_0 - m_0\overline{\psi}_0\psi_0 + g_0 A_0{}^\nu\overline{\psi}_0\gamma_\nu\psi_0 + ... \tag{3}$$

In perturbation theory, the interactions give rise to quantum corrections to the bare quantities, which turn out to be infinite. These infinities can be handled by the procedure of renormalization, where the bare Lagrangian is split up into an infinite and a finite part at a specified energy scale E :

$$L_0 = [L_0 - \delta L(E)] + \delta L(E) \tag{4}$$

$\delta L(E)$ is the measurable part of the Lagrangian, which has the same form as L_0 :

$$\delta L = i\overline{\psi}\gamma_\nu\partial^\nu\psi - m(E)\overline{\psi}\psi + g(E)A^\nu\overline{\psi}\gamma_\nu\psi + ... \tag{5}$$

but with all the terms now finite. The physical requirement that the bare quantities can not depend on the arbitrary scale E leads to the renormalization group equations (RGEs) for the parameters such as masses, coupling constants and field normalizations. The classic example of the application of RGEs to the strong coupling constant, g_3 :

$$\frac{\partial g_3}{\partial \ln E^2} = -\frac{g_3^3}{16\pi^2}\left(\frac{11}{3}N_C - \frac{4}{3}\frac{N_F}{2}\right) + O(g^5) \tag{6}$$

where N_C is the number of colours and N_F is the number of quarks contributing to the radiative corrections. The famous minus sign in this equation led to the understanding of asymptotic freedom in quantum chromodynamics. RGEs similar to Equation (6) also apply to the $SU(2)_L$ coupling g_2 and the $U(1)_Y$ coupling g_1. By defining

$$\alpha_i \equiv \frac{g_i^2}{(4\pi)^2} \tag{7}$$

the RGEs for the α_i then have the form

$$\frac{\partial}{\partial(\log E)}\left(\frac{1}{\alpha_i}\right) = k_i \tag{8}$$

for constants k_i , whose values depend on the couplings and matter content in the entire theory; the couplings "run" with the energy scale. Thus by plotting α_i^{-1} against $\log E$, a straight line is obtained whose slope, k_i , depends on the matter and couplings of the entire theory. Inputting the SM particles and couplings into the RGEs the plot shown in Figure 1 (Left) is obtained. The fact that the three lines are tending to meet at a common energy scale is suggestive of grand unification taking place at a GUT scale of about 10^{15} GeV; however the interception is not exact and a GUT scale of this magnitude is too low to account for the measured lower limits on proton lifetime; in GUTs proton decay is mediated by heavy gauge particles whose mass is the same order of magnitude as the GUT scale.

Both these problems are resolved by the introduction of more particle content into the RGEs, such as occurs in SUSY as described in Section 5.

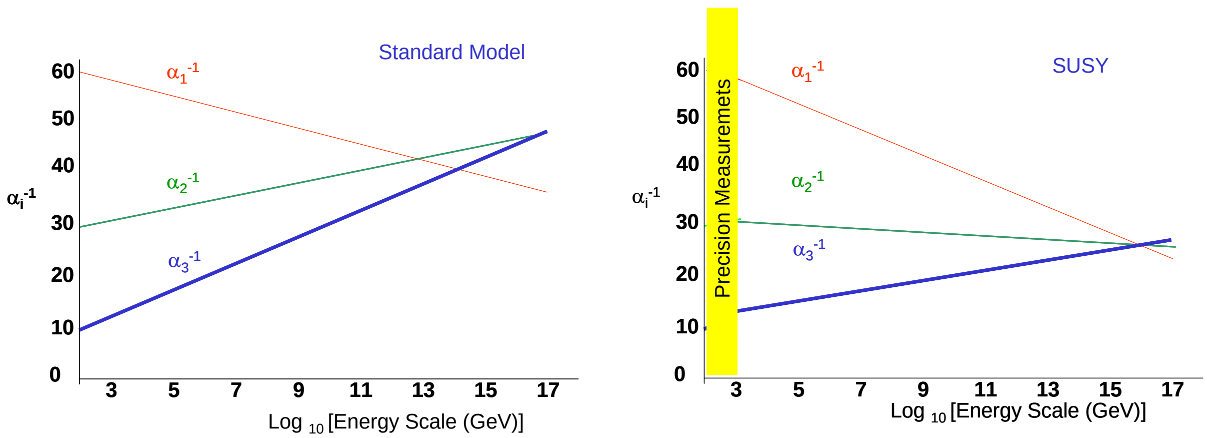


Figure 1. Left: The RGE evolution ("running") of the gauge fine structure parameters as a function of energy scale for SM particle content. Right: the running of the gauge fine structure parameters in SUSY theories. The energy scale at which precision measurements will be made at the LHC and ILC is indicated for illustrative purposes.

4. ELECTROWEAK SYMMETRY BREAKING

The SM requires that the $SU(2)_L \times U(1)_Y$ symmetry gets broken down to $U(1)_{EM}$. Perhaps the simplest mechanism of electroweak symmetry breaking is via the Higgs mechanism, where a fundamental scalar field ϕ gains a non-zero vacuum expectation value $\langle\phi\rangle \neq 0$ that both breaks the symmetry and provides a background field to which other fields couple and thereby gain their mass. The Lagrangian for ϕ is given in Eq. 1

$$L = \partial_\mu \phi\ \partial^\mu \phi + \mu^2 \phi^2 + \lambda \phi^4 \tag{9}$$

It must be that $\lambda > 0$ in order that the potential is bounded from below, but it is possible that $\mu^2 < 0$ and in this case the potential has the well-known Mexican hat form, where the lowest value of the potential occurs at a non-zero value of ϕ, giving $\langle\phi\rangle \neq 0$ and thereby breaking the electroweak symmetry.

A problem arises in this model when interactions are turned on in perturbation theory. The renormalization effects introduced in Section 3 give corrections to the higgs mass that are quadratic in the energy scale. Such quadratic divergences do not occur for the fermionic fields of the SM because there is a protective chiral symmetry that forbids mass-terms such as $\overline{\psi}_L \psi_R$ being generated by radiative corrections. As a result, there is no symmetry to keep the Higgs mass lighter than the next scale of new physics, which could be the GUT or the Planck scale, without extreme fine tuning of the SM parameters.

5. SUPERSYMMETRY

Supersymmetry (SUSY) is a symmetry that relates the fermionic and bosonic content of the theory. In SUSY theories, for each SM fermionic spin-½ field there is bosonic spin-0 partner with exactly the same gauge quantum numbers. Similarly, each SM spin-1 field has a SUSY spin-½ partner. The Lagrangian is then made symmetric under SUSY transformations that turn fermions into bosons and vice-versa. In this way SUSY uses indirectly the already-present chiral symmetries to protect the masses of the scalars in the theory. The Higgs mass is then protected against quadratic divergences and can be kept light naturally, without fine tuning.

In addition to allowing a naturally light Higgs field, the additional particle content in SUSY also allows an RGE evolution of the gauge couplings such that they meet at a common point – and also at a higher GUT scale, which in turn naturally suppresses the rate of proton decay. This new evolution is illustrated schematically in Figure 1 (Right).

While SUSY provides an elegant solution to the Higgs mass problem introduced by the heierarchy between the GUT and electroweak energy scales, it needs to be broken at low energy scales since no SUSY particles have the same masses as their SM counterparts. While it would be natural to attempt to break SUSY by a Higgs-like mechanism, the Ferarra-Girardello-Palumbo sum rule [1]:

$$\sum_{\text{Spin J}} (-1)^J (2J+1) M_J^2 = 0 \tag{10}$$

would require at least one SUSY field to be lighter than its SM partner, which is in conflict with observation. As a result, SUSY breaking must take place in a hidden sector and be mediated to the observable sector by an indirect mechanism. The result of this breaking can be parameterized in terms of “soft breaking” parameters, so called because while they break SUSY, they do not do so in a way that can introduce quadratic divergences back into the theory. The general form for these soft breaking terms for the SUSY scalar fields is given in Equation 11:

$$V_{scalar} = \sum_j \left| \frac{\partial W}{\partial \phi_j} \right|^2 + V_D + \sum_{i,j} m_{i,j}^2 \phi_i^* \phi_j + A_U h_U Q_L H_2 U_R + A_D h_D Q_L H_1 D_R + A_E h_E L_L H_1 E_R + B\mu H_1 H_2 \tag{11}$$

The Ah terms are 3 × 3 matrices in general acting across generations. Once the sign of the μ term is specified, its magnitude can be calculated by requiring electroweak symmetry breaking to occur correctly. Corresponding soft breaking terms for the SUSY gauge (gaugino) sector are parameterized by the three gaugino masses M_1, M_2, M_3 which give rise to the following mass-matrices for the charged gauginos $\tilde{\chi}_{1,2}^{\pm}$ (which are mixtures of the SUSY partners of the $W^{\pm}$ and the charged Higgses), the neutralinos $\tilde{\chi}_{1-4}^{0}$ (which are mixtures of the SUSY partners of the Z^0, γ and neutral Higgses), and the gluino $\tilde{g}$ (the SUSY partner of the gluon).

$$M_{\tilde{\chi}^+} = \begin{pmatrix} M_2 & \sqrt{2} m_W c_\beta \\ \sqrt{2} m_W s_\beta & \mu \end{pmatrix} \tag{12}$$

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix} \tag{13}$$

$$M_{\tilde{g}} = M_3 \tag{14}$$

where the notation is that $c_\beta = \cos\beta$ etc., where $\tan\beta$ is the ratio of the two neutral Higgs vacuum expectation values (in SUSY two Higgs fields are required; one to give masses to up-type fields and one to down-type fields).

The scalar-fermion $\tilde{f}$ masses are parameterized by

$$M_{\tilde{f}}^2 = \begin{pmatrix} m_{\tilde{f}_L}^2 & m_f a_f \\ m_f a_f & m_{\tilde{f}_R}^2 \end{pmatrix} \tag{15}$$

$$m_{\tilde{f}_L}^2 = M_{\tilde{F}_L}^2 + (T_f^3 - e_f \sin^2\theta_W)\cos 2\beta m_Z^2 + m_f^2 \tag{16}$$

$$m_{\tilde{f}_R}^2 = M_{\tilde{F}_R}^2 + e_f \sin^2\theta_W \cos 2\beta m_Z^2 + m_f^2 \tag{17}$$

$$\begin{aligned} a_t &= A_t - \mu\cot\beta \\ a_b &= A_b - \mu\tan\beta \\ a_\tau &= A_\tau - \mu\tan\beta \end{aligned} \tag{18}$$

The SUSY spectrum depends on the values of these soft-breaking parameters, which in turn arise from the specific mechanism of SUSY breaking employed. A variety of mediating mechanisms have been proposed, including gravity mediated (e.g. minimal supergravity or mSUGRA) theories, gauge-mediated SUSY breaking (GMSB) theories, and anomaly mediated (AMSB), among others; some representative spectra are shown in Figure 2 (Left).

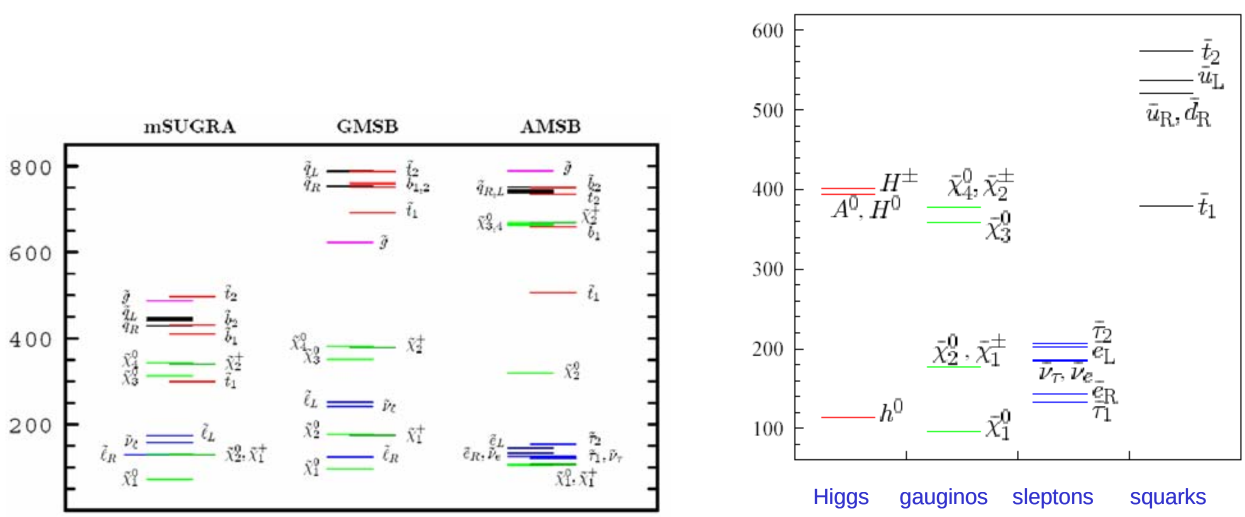


Figure 2.Left: Some typical SUSY mass spectra arising from different mechanisms of SUSY breaking. Right: the detailed spectrum for the MSSM point SPS1a.

The Minimal Supersymmetric Standard Model (MSSM) is a generic expression for the models based on a minimal set of soft breaking parameters; the scalar mass parameter M_0, the gaugino mass parameter $M_{1/2}$, the tri-linear term A, $\tan\beta$ and the sign of μ. A set of such points have been defined [2] for the purposes of studying generic experimental cases in order to optimise detector performances and possible collider running modes. One such point, called SPS1a has $M_0 = 100\,\text{GeV}$, $M_{1/2} = 250\,\text{GeV}$, $A = -100\,\text{GeV}$ and sign(μ) = +. These parameters are defined at the GUT scale; their values at the electroweak scale will be different because, in common with all Lagrangian parameters, their values will run with energy scale according to the RGEs for the theory. SPS1a will be used in the next section to discuss experimental prospects for exploring SUSY at future colliders. The particle spectrum for this model is shown in Figure 2 (Right).

6. EXPERIMENTAL PROSPECTS

The next decade will bring a step-change in our understanding of physics at the TeV scale, as the LHC gets up to full luminosity, colliding protons at a centre of mass energy of 14 TeV. Two general purpose detectors (in addition to two other detectors; ALICE specialized for heavy-ion collisions and LHC-b specialized for studying b-physics) will study the final states resulting from these collisions; ATLAS and CMS. ATLAS is shown in Figure 3 (Left); it has diameter 25m and total weight of 7000 tonnes. The other general purpose detector, CMS, has diameter 15m and total weight 12,500 tonnes. Both detectors will be well-equipped to search for SUSY events, as discussed below.

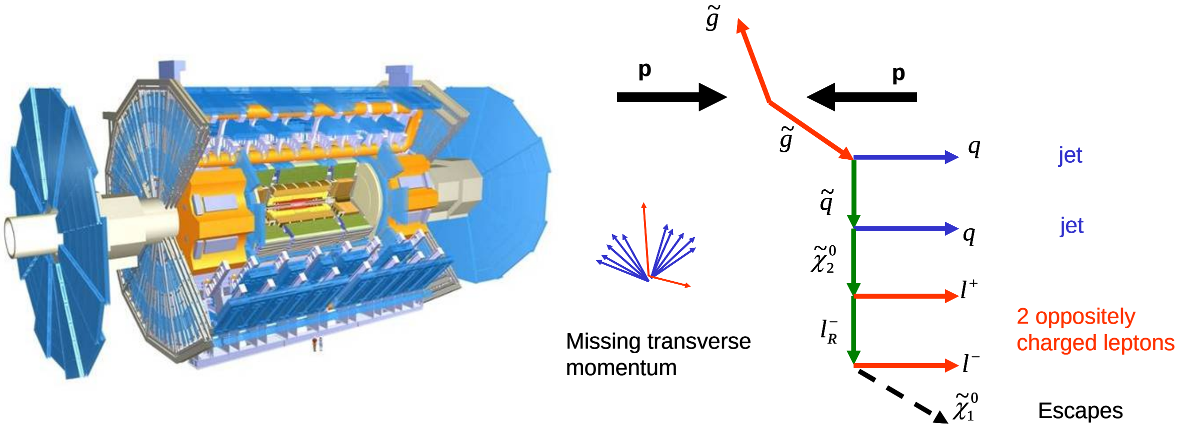


Figure 3. Left: schematic of the ATLAS detector at the LHC. Right: schematic of a typical SUSY event; the typical signature is missing transverse momentum accompanied by high-momentum jets and leptons.

The fundamental collision at a proton collider is between the constituent quarks or gluons. As a result, the exact centre of mass energy $\sqrt{s}$ is not known but the total transverse momentum is zero. This gives the key to identifying SUSY events, because a large amount of missing energy/momentum is carried away by the neutralinos in the final state; these are only weakly interacting and so will escape the detector. The underlying event is in general complicated by the presence of cascade decays as shown for the case of gluino production in Figure 3 (right). In order to understand the underlying event, invariant mass distributions of the final state products can be constructed and the particle masses inferred by determining the end-points of such distributions. An example is shown in Figure 4 (left) where the jet-lepton-lepton invariant mass is plotted for the case of gluino mass production at the LHC in the model SPS1a.

In contrast the ILC will collide elementary particles (electrons and positrons) so $\sqrt{s}$ is known precisely , which provides an important constraint when reconstructing kinematic variables. This is illustrated in Figure 4 (right) where the energy is plotted of the final state muons from the process $e_L^+ e_R^- \to \tilde{\mu}_R^+ \tilde{\mu}_R^- \to \mu^+ \chi_1^0 \mu^- \chi_1^0$. The sharp endpoints enable both the mass of the smuon and the mass of the lightest neutralino to be obtained with high precision, as listed in Table I.

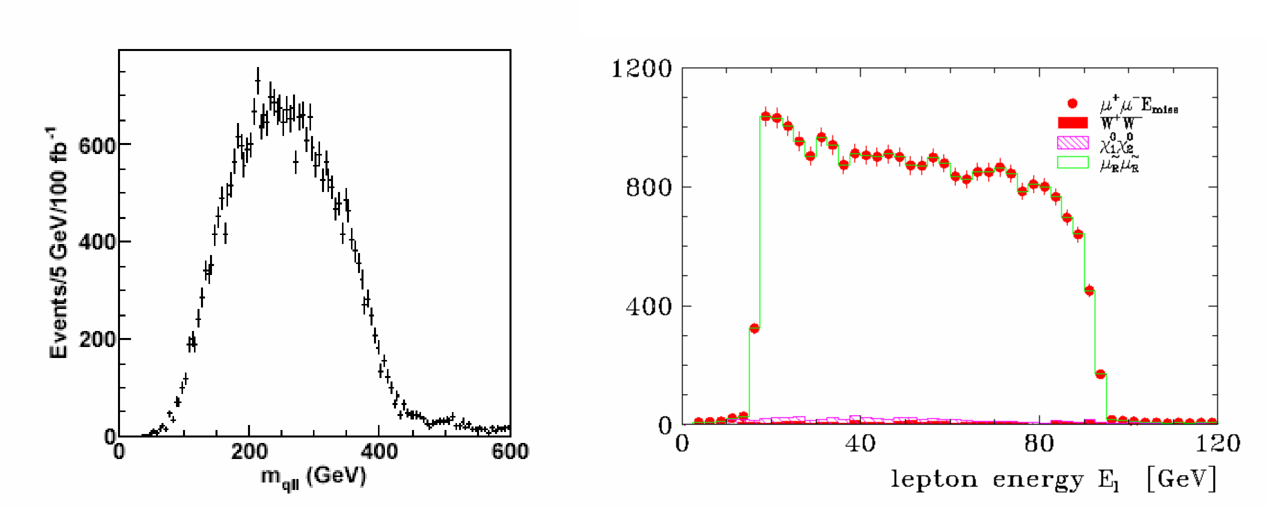


Figure 4: Left: invariant mass distribution of the jet plus two leptons from gluino decay at the LHC, using 100 fb^{-1} of data and assuming the SPS1a model. Right: muon energy distribution from smuon production at the ILC with CMS 400 GeV and 200 fb^{-1} of data [3].

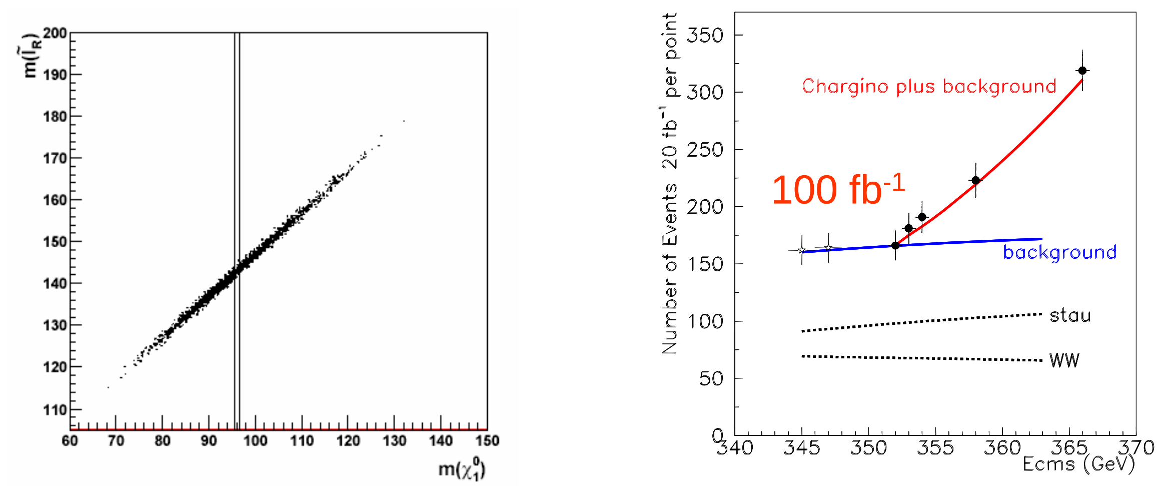


Figure 5. Left: Correlations at the LHC between the masses of the right-handed sleptons and the lightest neutralino. By measuring the latter to high precision at the ILC, the error on the former can be reduced dramatically [3]. Right: threshold scans at the ILC can be used to make very high precision mass measurements; illustrated is the case for chargino production in SPS1a where the process is $e_L^+ e_R^- \to \chi_1^+ \chi_1^- \to \tau^+ \chi_1^0 \tau^- \chi_1^0$ [3].

The very high precision determination at the ILC of the lightest neutralino (χ_1^0) mass will input into many LHC analyses, where the χ_1^0 appears at the end of all the decay chains (assuming R-parity to hold), resulting in a strong correlation between the χ_1^0 mass and other masses determined at the LHC. By knowing this mass precisely, these correlations can be resolved, as illustrated in Figure 5 (left). An additional advantage of the ILC is that $\sqrt{s}$ can be varied precisely so that the shape of the pair production cross section at threshold can be determined to high precision. By fitting the shape of this excitation curve to the mass of the pair-produced particles, a very accurate determination of the particle mass is possible. This technique works especially well for the production of spin-½ particles (gauginos) in the *s*-channel where the production threshold increases sharply, being proportional to the relativistic $\beta = v/c$. In contrast, scalar particle production turns on as β^3 so threshold scans are less favourable compared to the end-point determinations discussed above. However a sharp threshold can be obtained for $\tilde{e}_R^- \tilde{e}_R^-$ by operating the ILC in electron-electron mode [4].

By combining LHC measurements with those from the ILC, the optimal errors on the particle masses can be determined, as illustrated in Table I.

Table I: Representative experimental mass errors at LHC and ILC separately, and also by combining analyses from both colliders. The spectrum assumed is that for mSUGRA point SPS1a. All units in GeV/c^2

Particle	**Mass**	**LHC**	**ILC**	**LHC+ILC**
$\tilde{\chi}_1^{\pm}$	181.5	-	0.55	0.55
$\tilde{\chi}_2^{\pm}$	381.2	-	3.0	3.0
$\tilde{\chi}_1^0$	97.7	8.4	0.05	0.05
$\tilde{\chi}_2^0$	183.0	8.2	1.2	0.08
$\tilde{\chi}_3^0$	363.3	-		
$\tilde{\chi}_4^0$	381.0	8.9		2.0
$\tilde{e}_R$	143.9	8.4	0.05	0.05
$\tilde{e}_L$	206.6	8.8	0.2	0.2
$\tilde{\nu}_e$	190.5	-	0.7	0.7
$\tilde{\mu}_R$	143.8	8.4	0.2	0.2
$\tilde{\mu}_L$	206.6	8.8	0.5	0.5
$\tilde{\nu}_\mu$	190.4	-		
$\tilde{\tau}_1$	134.5	8.6	0.3	0.3
$\tilde{\tau}_2$	210.4	-	1.1	1.1
$\tilde{\nu}_\tau$	189.6	-	-	-
$\tilde{u}_R$	547.8	13.6	-	7.4
$\tilde{u}_L$	564.9	13.8	-	3.3

7. REPRESENTATIVE RGE EXTRAPOLATIONS

Once the particle spectrum has been determined using data from the LHC and ILC, the MSSM parameters can be extracted by inverting Equations (12)-(18) above. In addition to providing the MSSM parameters themselves, the knowledge of the particle spectrum and couplings enables the RGEs to be determined and this in turn enables the parameters measured at the electroweak scale to be extrapolated to the GUT scale. In the following sections this bottom-up approach is illustrated for two representative cases of SUSY breaking; mSUGRA and GMSB. An example of the top-down approach is also provided for a string-effective theory.

7.1. Minimal Supergravity

The mass spectrum of the spin-½ partners of the gauge bosons (the gauginos) is determined by the gaugino mass parameters M_1, M_2 and M_3 which, analogously to the gauge coupling parameters, should meet after RGE extrapolation at a common point at the GUT scale. This behavior, for SPS1a, is illustrated in Figure 6.

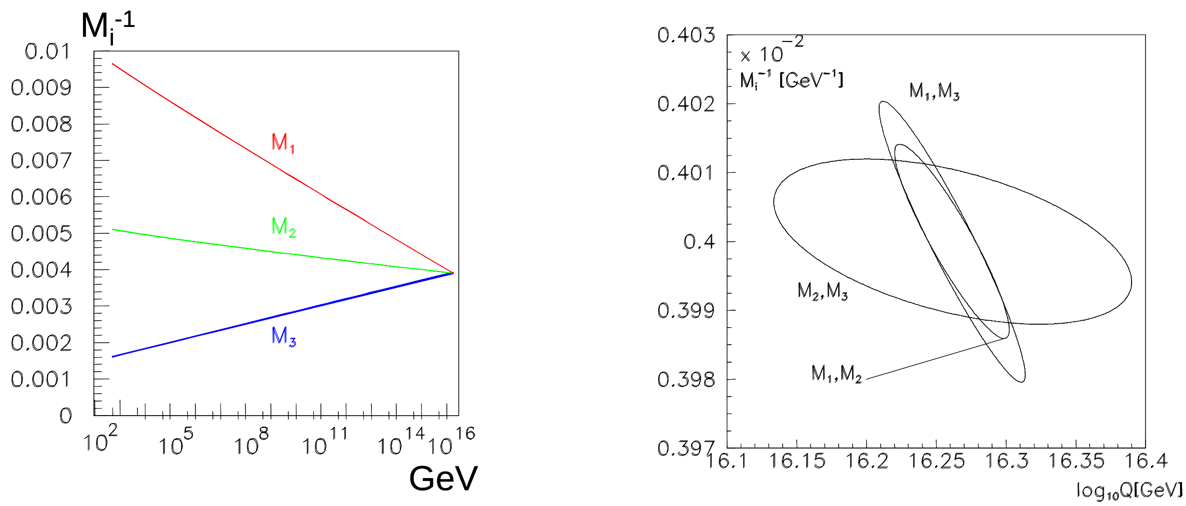


Figure 6. Left: extrapolation of the reciprocals of the SPS1a gaugino mass parameters from the electroweak scale to the GUT scale using the RGEs with experimental input from prospective measurements at the LHC and ILC. Right: the intersection ellipses of the gaugino parameters at the GUT scale, which are formed by intersecting in independent pairs the error bands from the RGE expansion.

In mSUGRA, the scalar parameters should also meet at the same scale, since there is only one relevant scale present (the GUT scale, close to the Planck scale) due to the fact that gravity is blind to the gauge and flavour quantum numbers. This behaviour is shown clearly in Figure 7, where the error bands meet at a common point for all the squark, slepton and higgs mass breaking parameters

7.2. Gauge Mediated Supersymmetry Breaking

In the case of GMSB, SUSY breaking is mediated from the hidden sector via a new set of messengers fields that couple to the gauge quantum numbers and break SUSY at a new energy scale, the messenger scale M_m. This mechanism will give rise to new experimental signatures [5] and also yield a different spectrum from mSUGRA at the electroweak scale. Furthermore, in this scenario regular soft-breaking parameter values are not expected to emerge at the GUT scale because the fields gain their masses instead at M_m, not M_{GUT}, with values that depend on their gauge quantum numbers. This behaviour is demonstrated in Figure 8 (Left) for the GMSB point M_m= 200 TeV, Λ = 100TeV, N_5 = 1, $\tan\beta$ = 15, sign(μ) = +, where after extrapolation to the GUT scale, the curves do not meet at a point at M_{GUT}.

The fields L_1 and H_2 have the same SU(2) × U(1) gauge quantum numbers and so will have the same value of their soft breaking terms at M_m. This fact enables the messenger scale to be determined by the intersection of the RGE-extrapolated error bands, as illustrated in Figure 8 (Right).

.

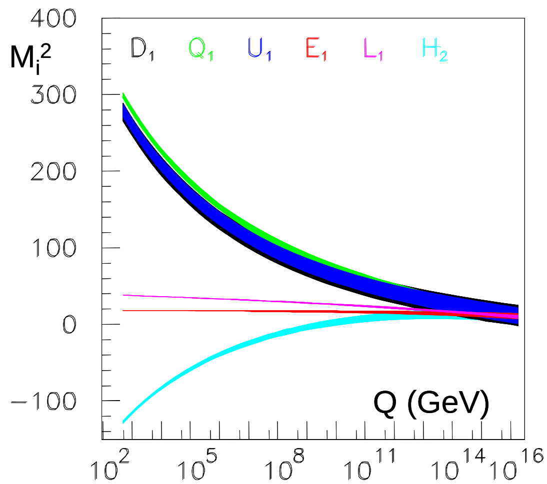
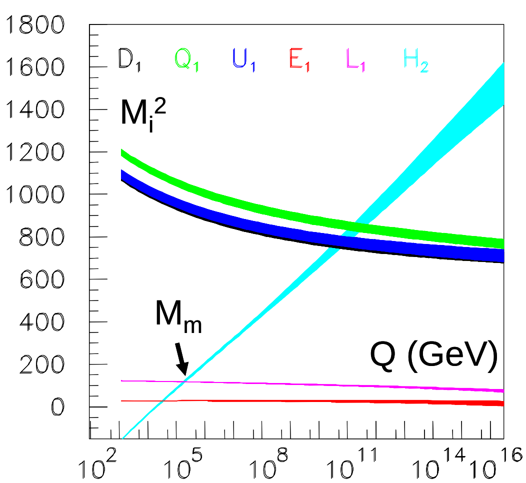


Figure 7. Model-independent RGE extrapolation of SPS1a scalar parameters from the electroweak scale to the GUT scale using the RGEs with experimental input from prospective measurements at the LHC and ILC [6].



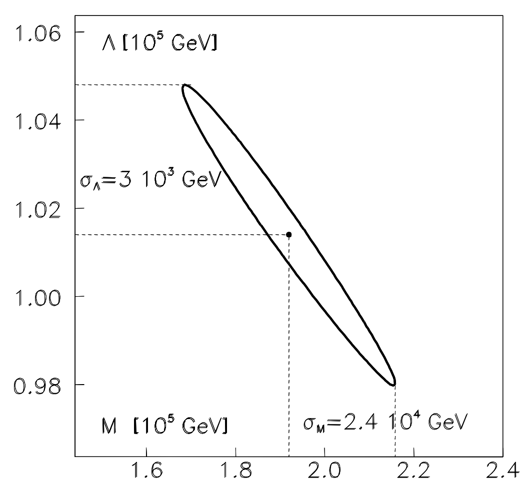


Figure 8. Left: Model-independent RGE extrapolation of scalar mass parameters for GMSB point M_m=200 TeV, Λ=100 TeV, N_5=1, $\tan\beta$=15, sign(μ) = +. Right: The error ellipse at the intersection of the L_1 and H_2 mass parameters; these have the same gauge quantum numbers and so should have the same value at the messenger scale M_m.

7.3. String Effective Theory

When discussing RGE extrapolation of low-energy parameters to the GUT scale, the proximity of the GUT and Planck scales suggests that any theory that provides a more consistent treatment of particle physics and gravity (such as string theory) may also provide predictable corrections to the soft breaking parameters at the GUT scale. A candidate string effective theory has been explored [6] in this context; in this theory the soft breaking spectrum is determined by a new set of parameters, including integer-valued modular weights. In this effective theory, the bottom-up RGE extrapolation of the gaugino parameters does not show a meeting point at the GUT scale (the latter being defined by the intersection of the gauge coupling parameters) because the universality is broken by string threshold corrections, as shown in Figure 9. Once such a generic string-inspired model has been established, the detailed parameters can then be determined by a top-down fit to the string parameters. A representative set of the resulting fit errors is shown in Table II, which shows that the integer nature of the modular weights n_i can in principle be determined experimentally, given the prospective particle mass measurement accuracy at the LHC/ILC.

Table II: Representative errors on the parameters from a string effective theory, using as input the experimental errors that may be obtained at the LHC and ILC [6].

Parameter	Ideal	Reconstructed
$m_{3/2}$	180	179.9 ± 0.4 GeV
$\langle S \rangle$	2	1.998 ± 0.006 TeV
$\langle T \rangle$	14	14.6 ± 0.2 TeV
Sin2θ	0.9	0.899 ± 0.002
G_s^2	0.5	0.501 ± 0.002
δ_{GS}	0	0.1 ± 0.4
n_L	-3	-2.94 ± 0.04
n_E	-1	-1.00 ± 0.05
n_Q	0	0.02 ± 0.02
n_U	-2	-2.01 ± 0.02
n_D	1	0.80 ± 0.04
n_{H1}	-1	-0.96 ± 0.06
n_{H2}	-1	-1.00 ± 0.02
Tanβ	10	10.00 ± 0.13

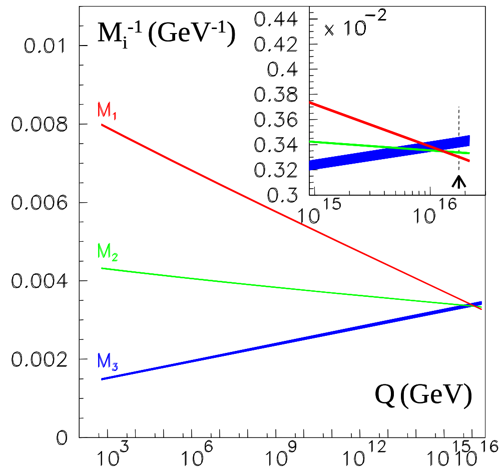


Figure 9. Model-independent bottom-up RGE extrapolation for a representative string effective theory. Universality at the GUT scale has been broken by string threshold corrections.

8. SUMMARY

Some of the major problems raised by the Higgs mechanism of electroweak symmetry breaking can be alleviated by the introduction of SUSY. If SUSY is indeed realized in nature, then its breaking will require a new mechanism for SUSY mass generation and determining this mechanism should yield new insights into the structure of physics at very high energy scales, especially the GUT scale. Access to even higher scales (notably the Planck scale) may then be apparent through threshold corrections at the GUT scale, such as are predicted from string effective theories. If nature is to be probed at these very high energy scales using RGE extrapolation, then high precision measurements at the electroweak scale will be crucial. The first of such measurements will be performed at the LHC and, if eventually constructed, significant improvements and new insights will emerge from the ILC.

Ackowledgments

Support from SLAC to attend the Summer Institute is gratefully acknowledged. In addition, this work supported in part by grants from the British Council and the Royal Society.

References

[1] S. Ferrara, L. Girardello and F. Palumbo, Phys. Rev. **D20** (1979) 403.

[2] Supersymmetry Parameter Analysis (SPA) Project, http://spa.desy.de/spa/; J. A. Aguilar-Saavedra et al., hep-ph/0511344, B. C. Allanach et al., Eur. Phys. J. **C 25** (2002) 113.

[3] LHC/LC Study Group Working Report, eds.G. Weiglein et al., hep-ph/0410364; Phys.Rep. C in preparation.

[4] J.L. Feng and M.E. Peskin Phys.Rev.**D64:**115002,2001,
A. Freitas, D.J. Miller, P.M. Zerwas Eur.Phys.J.**C21:**361-368,2001

[5] S. Ambrosanio and G.A. Blair, Eur. Phys. J. **C12** (2000) 287.

[6] G. A. Blair, W. Porod and P. M. Zerwas, Phys. Rev. **D63** (2001) 017703 and Eur. Phys. J. **C27** (2003) 263.